10/15/04
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HFDA05 Test Summary

S. Feher, B. Bordini, G. Ambrosio, N. Andreev, R. Carcagno, D. Chichili, V.V. Kashikhin, M.J. Lamm, I. Novitski, D. Orris, Y. Pischalnikov, C. Sylvester, M. Tartaglia, J.C. Tompkins, G. Velev, A.V. Zlobin

Content:

1. Introduction

HFDA05 was completed on August 10, 2004. The magnet was installed into the VMTF dewar and it was electrically checked by the end of August 20th , 2004. The VMTF dewar was filled with liquid helium on September 7th. First thermal cycle of the magnet has been completed on September 10th . There were no modifications introduced for the second test cycle. The second thermal cycle was started on September 20th and it was finished on September 24th.

2. Quench History

The magnet program has started with training at 20 A/s ramp rate. The first quench was at relatively high current 14012A, much higher than any predecessor of the same kind. This magnet exhibited a slow but steady training. It took almost 23 quenches to train the it. The highest quench current at 4.5K (20A/s) was 16804A. After a successful training we continued the program with ramp rat studies followed by 2.2 K quench training. The magnet at 2.2 K reached more than 10 T magnetic field. After these low temperature quenches we warmed up the magnet to 4.5K and quenched the magnet again few times. At the second thermal cycle we verified that the magnet didn’t remembered its training. It took only couple of quenches to reach again the quench current plateau. In this test cycle we also performed temperature dependence studies, energy loss and splice measurements.

The quench history plot is presented in Figure 1. and in Table 1.

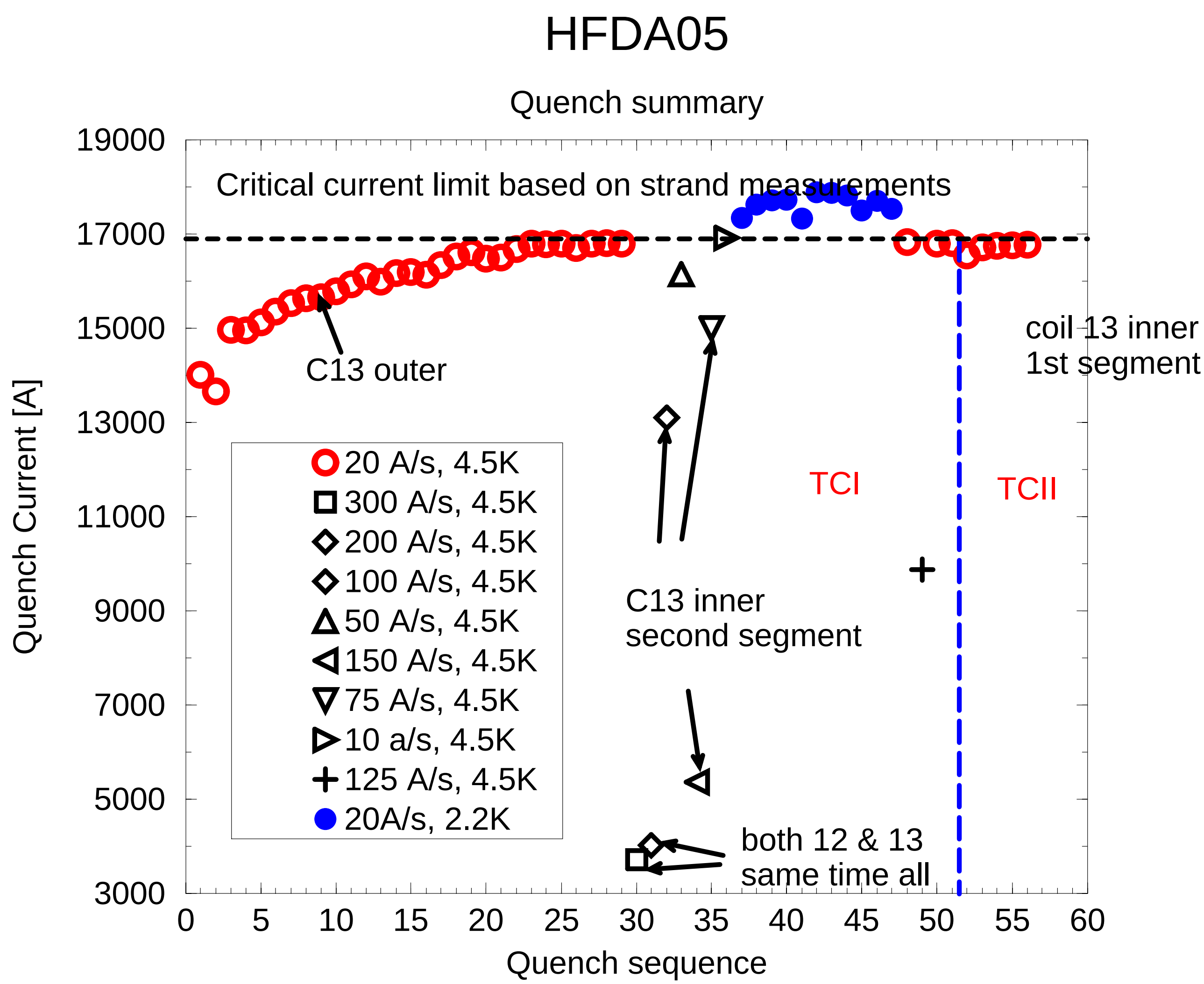

Figure 1. Quench history

Table I. hfda05 Quench Summary

File	Current (A)	dI/dt (A/sec)	t_{quench} (sec)	MIITs	QDC	1^{st} VTseg	t_{rise} (sec)	Mag Temp Bot Left (K)	Mag Temp Top Left (K)	Comment
hfda05.Quench.040907152236.783	1002	0	0.0011	0.08	WcoilGnd	Q14i12_Q1i12	0.0022	4.569	4.569	1000A manual trip
hfda05.Quench.040907155515.447	1001	0	0.0010	0.08	WcoilGnd	Q14i13_Q19i13	0.0021	4.568	4.565	1000A manual trip
hfda05.Quench.040907163720.010	5018	0	-0.0500	2.37	WcoilGnd	Q14i13_Q19i13	0.0013	4.562	4.561	5000A heater induced quench, SHFU=300V
hfda05.Quench.040907170314.563	14047	20	-0.0063	9.21	HcoilHcoil	Q1i13_Q14i13	-0.0049	4.564	4.567	1st quench, Iq=14012A, 20A/sec, 4.5K
hfda05.Quench.040907173040.026	13695	20	-0.0056	8.66	HcoilHcoil	Q1i13_Q14i13	-0.0049	4.568	4.566	2nd quench, Iq=13659A, 20A/sec, 4.5K
hfda05.Quench.040907175520.338	15001	0	-0.0031	9.69	HcoilHcoil	Q1i13_Q14i13	-0.0027	4.566	4.570	3rd quench, Iq=14964A, 20A/sec, 4.5K
hfda05.Quench.040907182553.467	14997	20	-0.0046	9.94	HcoilHcoil	Q1i13_Q14i13	-0.0025	4.563	4.565	4th, iq=14961A, 20A/sec, 4.5K
hfda05.Quench.040907185735.967	15169	20	-0.0041	9.92	HcoilHcoil	Q1i13_Q14i13	-0.0027	4.562	4.562	5th quench, Iq=15130A, 20A/sec, 4.5K
hfda05.Quench.040907192841.776	15388	20	-0.0027	9.89	HcoilHcoil	Q1i13_Q14i13	-0.0014	4.560	4.559	6th, Iq=15349A, 20a/sec, 4.5K
hfda05.Quench.040907195849.743	15571	20	-0.0025	10.01	HcoilHcoil	Q1i13_Q14i13	-0.0010	4.555	4.557	7th quench, 20A/s, 4.5K, Iq=15531A
hfda05.Quench.040907202852.592	15671	20	-0.0046	10.68	HcoilHcoil	Q1i13_Q14i13	-0.0031	4.554	4.557	8th, Iq=15632A, 20A/s, 4.5K
hfda05.Quench.040907205822.927	15700	20	-0.0126	12.92	HcoilHcoil	Q1i12_QMS1	0.0017	4.553	4.553	8th, Iq=1661A, 20a/sec, 4.5K
hfda05.Quench.040907213718.496	15820	19	-0.0025	10.25	HcoilHcoil	Q1i13_Q14i13	-0.0013	4.546	4.548	10th, Iq=15780A, 20a/s, 4.5K
hfda05.Quench.040908092248.934	15970	20	-0.0022	10.33	HcoilHcoil	Q1i13_Q14i13	-0.0013	4.525	4.526	11th, Iq=15929A, 20A/s, 4.5K
hfda05.Quench.040908095742.834	16136	20	-0.0017	10.41	HcoilHcoil	Q1i13_Q14i13	-0.0011	4.530	4.529	12th, Iq=16099A, 20A/sec, 4.5K
hfda05.Quench.040908103333.546	16030	-3045	-0.0027	10.52	HcoilHcoil	Q1i13_Q14i13	-0.0021	4.533	4.532	13th, Iq=15990A, 20A/sec, 4.5K
hfda05.Quench.040908110307.242	16211	20	-0.0017	10.43	HcoilHcoil	Q1i13_Q14i13	-0.0014	4.534	4.533	14th, Iq=16172A, 20A/s, 4.5K
hfda05.Quench.040908113337.811	16232	19	-0.0020	10.47	HcoilHcoil	Q1i13_Q14i13	-0.0014	4.535	4.535	15th, Iq=16190A, 20A/s, 4.5K
hfda05.Quench.040908120437.459	16180	20	-0.0027	10.61	HcoilHcoil	Q1i13_Q14i13	-0.0014	4.536	4.537	16th, Iq=16139A, 20a/sec, 4.5K
hfda05.Quench.040908131125.634	16385	20	-0.0015	10.59	HcoilHcoil	Q1i13_Q14i13	-0.0008	4.537	4.536	17th, Iq=16345A, 20A/s, 4.5Kto
hfda05.Quench.040908134849.500	16563	20	-0.0011	10.54	HcoilHcoil	Q1i13_Q14i13	-0.0003	4.538	4.540	18th, Iq=16520A, 20A/sec, 4.5K
hfda05.Quench.040908144557.459	16661	20	-0.0011	10.62	HcoilHcoil	Q1i13_Q14i13	-0.0001	4.535	4.538	19th quench, Iq=16620A, 20A/sec, 4.5K
hfda05.Quench.040908151843.144	16517	0	-0.0020	10.77	HcoilHcoil	Q1i13_Q14i13	-0.0014	4.533	4.537	20th, Iq=16474A, 20A/s, 4.5K
hfda05.Quench.040908154501.131	16535	20	-0.0017	10.73	HcoilHcoil	Q1i13_Q14i13	-0.0010	4.531	4.534	21th quench at I= 16494 A, 20 A/s
hfda05.Quench.040908161322.734	16727	20	-0.0017	10.84	HcoilHcoil	Q1i13_Q14i13	-0.0003	4.534	4.533	22nd quench Iq = 16687 A at 20 A/s
hfda05.Quench.040908164344.992	16840	20	-0.0024	11.03	HcoilHcoil	Q1i12_QMS1	0.0006	4.530	4.531	23rd quench Iq = 16794 A at 20 A/s
hfda05.Quench.040908171234.796	16829	20	-0.0020	10.90	HcoilHcoil	Q1i12_QMS1	0.0014	4.531	4.531	24th quench Iq = 16784 A at 20 A/s
hfda05.Quench.040908174629.875	16833	20	-0.0022	10.98	HcoilHcoil	Q1i13_Q14i13	0.0013	4.525	4.527	25th, Iq=16794A, 20A/s, 4.5K
hfda05.Quench.040908181831.546	16742	0	-0.0020	10.93	HcoilHcoil	Q1i13_Q14i13	-0.0011	4.527	4.526	26th, Iq=16703A, 20a/s, 4.5K
hfda05.Quench.040908184934.576	16846	20	-0.0020	10.91	HcoilHcoil	Q14i13_Q19i13	0.0001	4.522	4.524	Quench #27 Iq= 16802 A 20 A/sec 4.5 K
hfda05.Quench.040908192710.733	16847	20	-0.0025	11.11	HcoilHcoil	Q19i13_QNS2	-0.0008	4.515	4.520	28th, Iq~16500A, 20A/sec, 4.5K
hfda05.Quench.040908200841.918	16841	20	-0.0020	10.89	HcoilHcoil	Q14i13_Q19i13	0.0000	4.517	4.516	29th, Iq=16796A, 20A/s, 4.5K
hfda05.Quench.040908203012.433	3685	268	-0.1892	3.22	WcoilGnd	Q14i12_Q1i12	0.0010	4.511	4.503	30th, Iq=3715A, 300A/s, 4.5K
hfda05.Quench.040908204545.444	4029	200	-0.0650	1.40	WcoilIdot	Q14i13_Q19i13	-0.0496	4.504	4.504	31st, Iq=4019A, 200A/s, 4.5K
hfda05.Quench.040908210117.674	13140	100	-0.0022	7.27	HcoilHcoil	Q19i12_Q14i12	-0.0008	4.501	4.499	32nd, Iq=13105A, 100A/sec, 4.5K
hfda05.Quench.040908212617.017	16189	0	-0.0032	10.48	HcoilHcoil	Q14i13_Q19i13	-0.0003	4.504	4.503	33rd, Iq=16151A, 50A/s, 4.5K
hfda05.Quench.040908214759.255	5381	0	-0.0150	1.69	HcoilHcoil	Q14i12_Q1i12	-0.0106	4.501	4.497	34th, Iq=5366A, 150A/s, 4.5K
hfda05.Quench.040908221348.641	15042	75	-0.0024	9.24	HcoilHcoil	Q19i12_Q14i12	0.0011	4.497	4.496	35th, Iq=15003A, 75A/s, 4.5K

hfda05.Quench.040908225831.963	16970	10	-0.0052	12.19	WcoilIdot	Q1i13_Q14i13	-0.0006	4.506	4.509	36th, Iq=16926A, 10A/sec, 4.5K
hfda05.Quench.040909110027.803	17386	20	-0.0024	11.97	HcoilHcoil	Q1i13_Q14i13	-0.0013	2.149	2.148	37th quench, Iq=17340A, 20a/sec, 2.2K
hfda05.Quench.040909113310.798	17676	0	-0.0014	11.91	HcoilHcoil	Q1i13_Q14i13	0.0003	2.151	2.150	38th, Iq=17629A. 20a/sec, 2.2K
hfda05.Quench.040909120217.392	17761	20	-0.0087	14.16	HcoilHcoil	Q1i13_Q14i13	-0.0008	2.150	2.149	39th, Iq=17717A, 20A/S, 2.2K
hfda05.Quench.040909123025.273	17776	0	-0.0015	11.92	HcoilHcoil	Q1i13_Q14i13	-0.0011	2.148	2.149	40th, Iq=17127A, 20A/s, 2.2K
hfda05.Quench.040909134557.651	17378	20	-0.0018	11.80	HcoilHcoil	Q1i13_Q14i13	-0.0004	2.149	2.148	41st, Iq=17331A, 20A/s, 2.2K
hfda05.Quench.040909141736.671	17939	20	-0.0024	12.34	HcoilHcoil	Q1i13_Q14i13	-0.0006	2.151	2.150	42nd, Iq=17893A, 20A/s, 2.2K
hfda05.Quench.040909144538.082	17921	20	-0.0013	12.12	HcoilHcoil	Q1i13_Q14i13	0.0000	2.147	2.145	Q# 43, 17875.6, 20A/sec, 2.2 K
hfda05.Quench.040909153445.141	17865	20	-0.0014	12.08	HcoilHcoil	Q19i12_Q14i12	0.0017	2.173	2.196	Quench 44th, 20A/sec, 2.2 K Iq= 1783? A, not over 17900 A
hfda05.Quench.040909160844.398	17547	20	-0.0029	12.27	HcoilHcoil	Q1i13_Q14i13	-0.0014	2.198	2.255	Quench #45th, Iq = 17500.5 A, 20 A/s, 2.2 K E-02
hfda05.Quench.040909164505.221	17760	0	-0.0021	12.38	HcoilHcoil	Q1i13_Q14i13	-0.0014	2.149	2.149	45th quench, Iq=17711A, 20a/sec up to 170000 then 5 A/sec, 2.2K
hfda05.Quench.040909171313.934	17579	20	-0.0021	12.07	HcoilHcoil	Q1i13_Q14i13	-0.0008	2.149	2.148	46th, 17536A, 20a/sec, 4.5K
hfda05.Quench.040910082808.269	16876	19	-0.0042	11.60	HcoilHcoil	Q1i13_Q14i13	0.0006	4.489	4.495	48th, Iq=16832A, 20A/s, 4.5K
hfda05.Quench.040910084630.709	9869	125	-0.2076	24.36	WcoilGnd	Q14i12_Q1i12	-0.0042	4.499	4.494	49th, Iq=9870A, 125A/s, 4.5K
hfda05.Quench.040910172334.286	16843	20	-0.0031	11.39	WcoilIdot	Q14i13_Q19i13	-0.0004	4.514	4.515	50th, Iq=16798A, 20A/s, 4.5K
hfda05.Quench.040910175114.730	16855	20	-0.0042	11.62	HcoilHcoil	Q1i13_Q14i13	0.0013	4.516	4.518	51st, Iq=16813A, 20a/s, 4.5K
hfda05.Quench.040920155900.855	1008	0	0.0013	0.08	WcoilGnd	Q19i13_QNS2	0.0032	4.599	4.600	1000A manual trip
hfda05.Quench.040920161156.839	5017	0	-0.1747	4.91	WcoilIdot	QMS6_Q1i13	-0.0801	4.594	4.593	5000A, heater induced quench
hfda05.Quench.040920163653.944	16588	20	-0.0074	12.40	HcoilHcoil	Q1i13_Q14i13	-0.0010	4.593	4.594	51st, Iq=16547A, 20A/s, 4.5K
hfda05.Quench.040920170405.703	16760	0	-0.0027	11.26	HcoilHcoil	Q1i13_Q14i13	-0.0015	4.591	4.594	52nd quench, Iq=16716A, 20A/s, 4.5K
hfda05.Quench.040920173629.397	16801	20	-0.0024	10.99	HcoilHcoil	Q1i12_QMS1	0.0006	4.587	4.592	53rd, Iq=16756A, 20A/s, 4.5K
hfda05.Quench.040920190243.607	16813	20	-0.0027	11.13	HcoilHcoil	Q19i13_QNS2	-0.0013	4.571	4.574	55th quench, Iq=16770A, 20a/sec, 4.5K
hfda05.Quench.040920193502.430	16817	20	-0.0031	11.19	HcoilHcoil	Q1i12_QMS1	0.0004	4.571	4.576	56th quench, Iq~16750A, 20A/s, 4.5K
hfda05.Quench.040920203035.681	16857	20	-0.0025	11.14	HcoilHcoil	Q1i12_QMS1	0.0015	4.529	4.526	57th, Iq=16812A, 20A/s, 4.5K
hfda05.Quench.040921144402.816	4015	0	-0.0060	0.45	WcoilGnd	Q19i12_Q14i12	-0.0052	4.550	4.547	4000A trip
hfda05.Quench.040922121528.700	4857	199	-0.0196	1.53	HcoilHcoil	Q14i13_Q19i13	-0.0060	4.491	4.488	Tripped during 1st AC loss measurement cycle @200Amps/sec.
hfda05.Quench.040923120717.342	17090	20	-0.0021	11.36	HcoilHcoil	Q1i12_QMS1	0.0010	4.135	4.197	58th, Iq=17044A, 20A/s, 4.2K
hfda05.Quench.040923132944.263	17219	20	-0.0021	11.49	HcoilHcoil	Q1i12_QMS1	0.0013	3.953	3.968	59th, Iq=17168A, 20A/sec, 3.95K
hfda05.Quench.040923142728.700	17423	20	-0.0021	11.67	HcoilHcoil	QMS4_QMS5	0.0011	3.639	3.724	60th, Iq=17300A, 20A/sec, 3.7K
hfda05.Quench.040923151908.733	17507	20	-0.0014	11.71	HcoilHcoil	Q1i13_Q14i13	-0.0004	3.415	3.505	61st quench, Iq=17460A, 20A/s, 3.456K
hfda05.Quench.040923160730.757	17721	20	-0.0021	11.95	HcoilHcoil	Q14i13_Q19i13	0.0003	3.145	3.208	62nd Quench, Iq=17800A, 20a/sec, 3.2K
hfda05.Quench.040923164322.049	17848	0	-0.0022	12.16	HcoilHcoil	Q1i12_QMS1	0.0011	2.936	2.998	^3rd, Iq=17798A, 20A/sec, 2.97
hfda05.Quench.040923173732.628	17955	0	-0.0018	12.21	HcoilHcoil	Q19i13_QNS2	-0.0013	2.766	2.807	64th, 17906A, 20A/s, T=2.782K
hfda05.Quench.040923182252.556	18062	0	-0.0024	12.36	HcoilHcoil	Q1i13_Q14i13	0.0011	2.546	2.600	quench#64 ramp=20A/sec T=2.566 Iq=18011A
hfda05.Quench.040923190411.352	18005	0	-0.0011	12.11	HcoilHcoil	Q1i13_Q14i13	-0.0004	2.320	2.403	Quench# 66 ramp=20A/sec T=2.349K Iq=17958A
hfda05.Quench.040923195503.622	18218	0	-0.0015	12.25	HcoilHcoil	Q14i13_Q19i13	0.0003	2.197	2.165	67th, Iq=18169A, 20A/sec, 2.2K
hfda05.Quench.040924115343.155	326	19	0.0008	0.05	WcoilGnd	Q14i13_Q19i13	0.0011	3.933	4.237	AQD coil trip due to high noise level
hfda05.Quench.040924121547.223	17135	29444	-0.0069	12.69	WcoilIdot	Q14i12_Q1i12	-0.0021	3.967	4.281	68th quench, Iq=17087A, 20A/s, 4.1K
hfda05.Quench.040924130159.635	16935	20	-0.0025	11.22	HcoilHcoil	Q1i13_Q14i13	0.0008	4.412	4.413	169th, 16893A, 20A/s, T=4.41K

3. Ramp Rate Dependence

Ramp rate dependence studies are summarized in Figure 2. Quench current decreases with increasing ramp rate following a continuous function. This behavior is another confirmation that the magnets are at critical current limits. The shape of this dependence at low current ramp rates suggests that the ramp rate dependence is dominated by the eddy currents losses in the cable which are quite large in these two coils (see Fig.xx). At ramp rates higher than 200 A/s the quench current drops dramatically and practically does not change with the current ramp rate. This behavior indicates that the magnet is limited by high losses and insufficient coil cooling conditions.

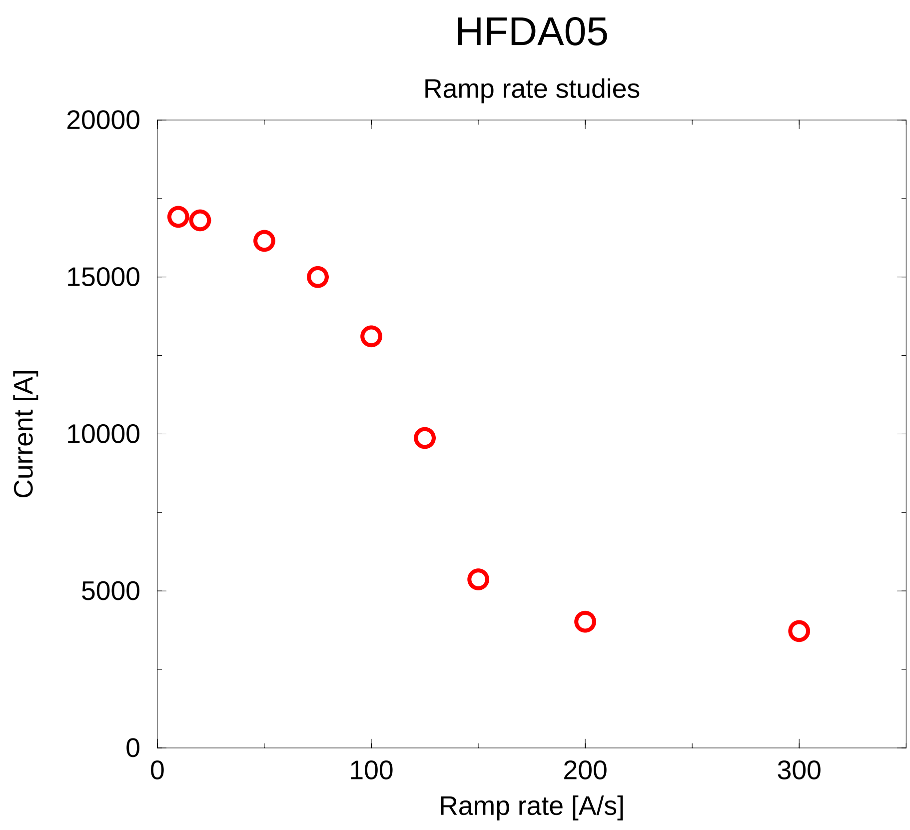

Figure 2. Current ramp rate dependence.

4. Temperature Dependence

Perfect temperature dependence was observed for HFDA05. The dependence of magnet quench current vs. temperature for HFDA05 is presented in Fig. 3. This dependence was measured during the second thermal cycle after the completion of magnet training at 4.5 K and 2.2 K. The data confirms that the magnet reached its short sample limit at all temperatures from 2.2 K to 4.5 K.

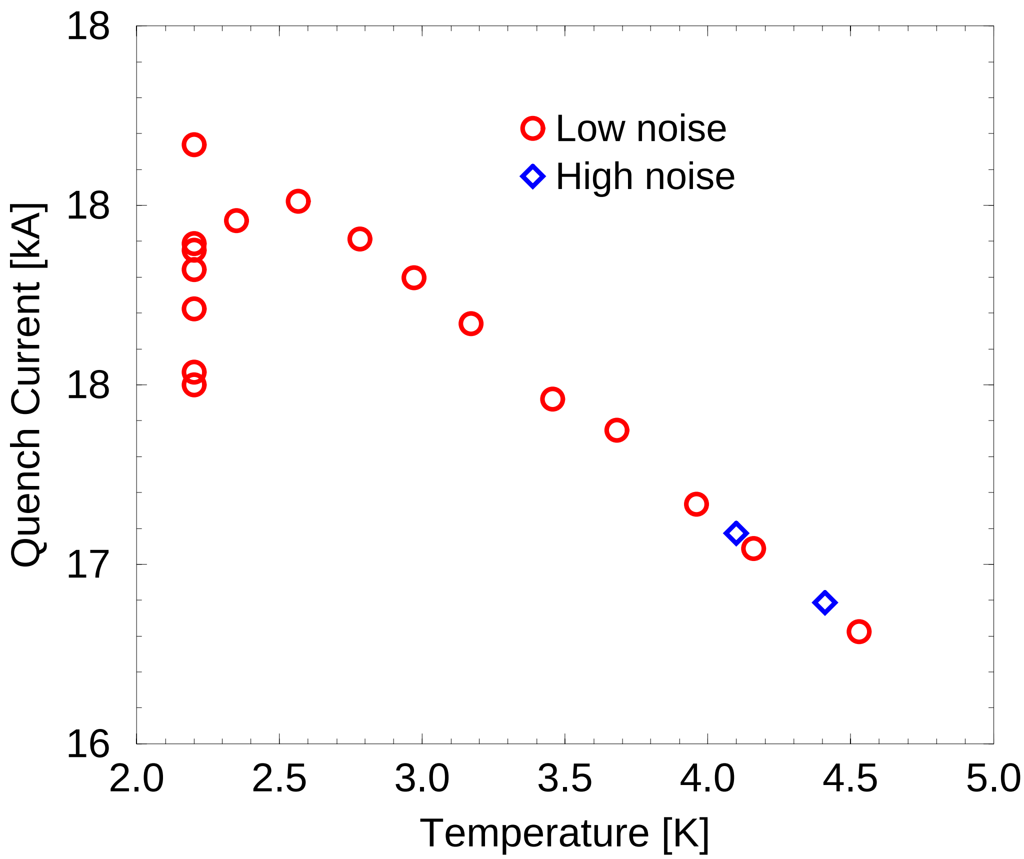

Figure 3. Temperature dependence studies.

5. Splice measurement

We performed splice measurements. The current was increased up to 16000 A and the voltage drops across the splices were recorded. Figure 4. shows the measurement results.

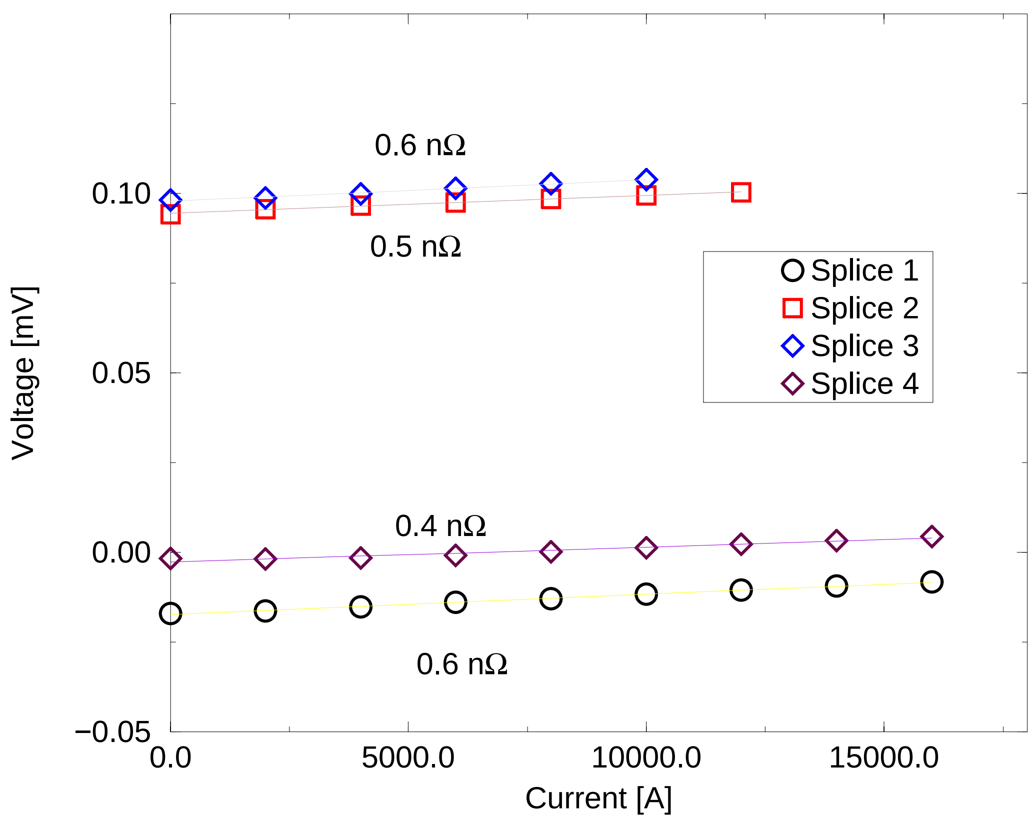

Figure 4. Splice measurement results

6. Magnetic measurement

Measurements of magnetic fields in the aperture were performed after cooling down in two thermal cycles. The measurement system was set up above VMTF cryostat and utilized 43 mm long probe (active length), 25 mm in diameter. The probe had a tangential winding for measurement of high order harmonics as well as dedicated dipole and quadrupole windings for measurement of low order harmonics. Voltages generated in the windings during the probe rotation were sampled and read 128 times per rotation using HP3458 DVMs. An additional DVM was used to monitor the magnet current. DVMs were triggered simultaneously by an angular encoder on the probe shaft, synchronizing measurements of the field and current. A probe centering correction was performed in assumption that unallowed by the dipole symmetry a_8 and b_8 harmonics were zero and there were no skew dipole component.

Z-scans

The Z-scans were performed with 43 mm steps at 4000 A during the ramps up and down following the pre-cycle up to 6000 A. Figure 5. presents the main field component averaged between the up and down ramps and Figures 6-9 show the averaged between up and down ramps low-order harmonics, normalized by the main field component at Z=0. There is a good reproducibility in the harmonics for the two thermal cycles.

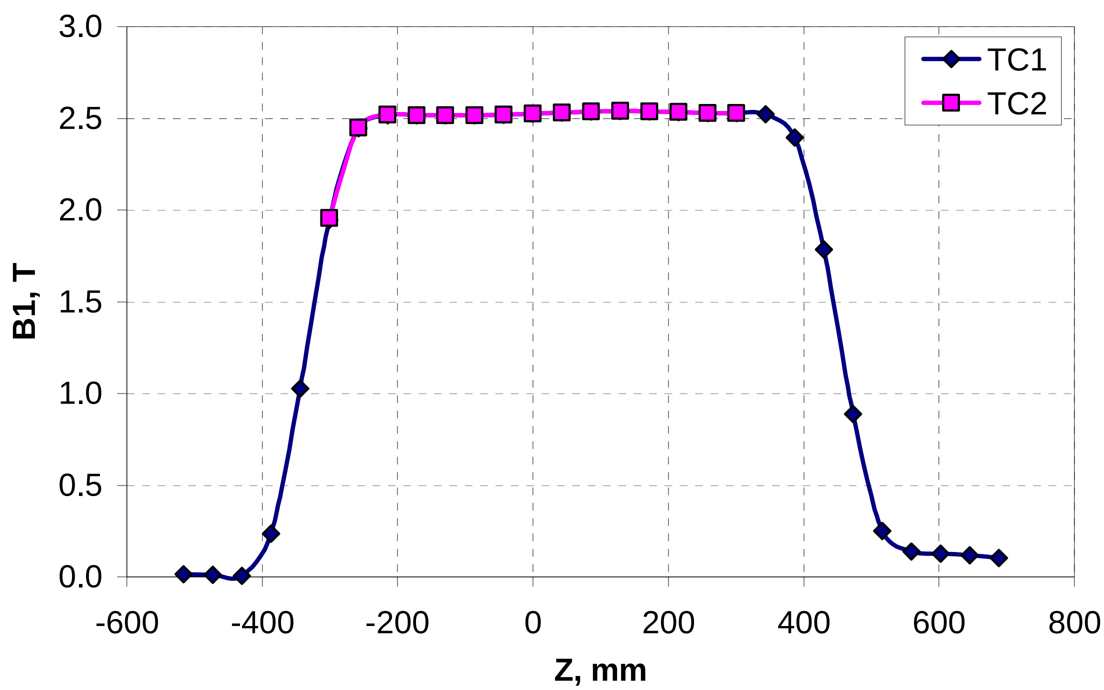

Figure 5. Main field component along Z-axis.

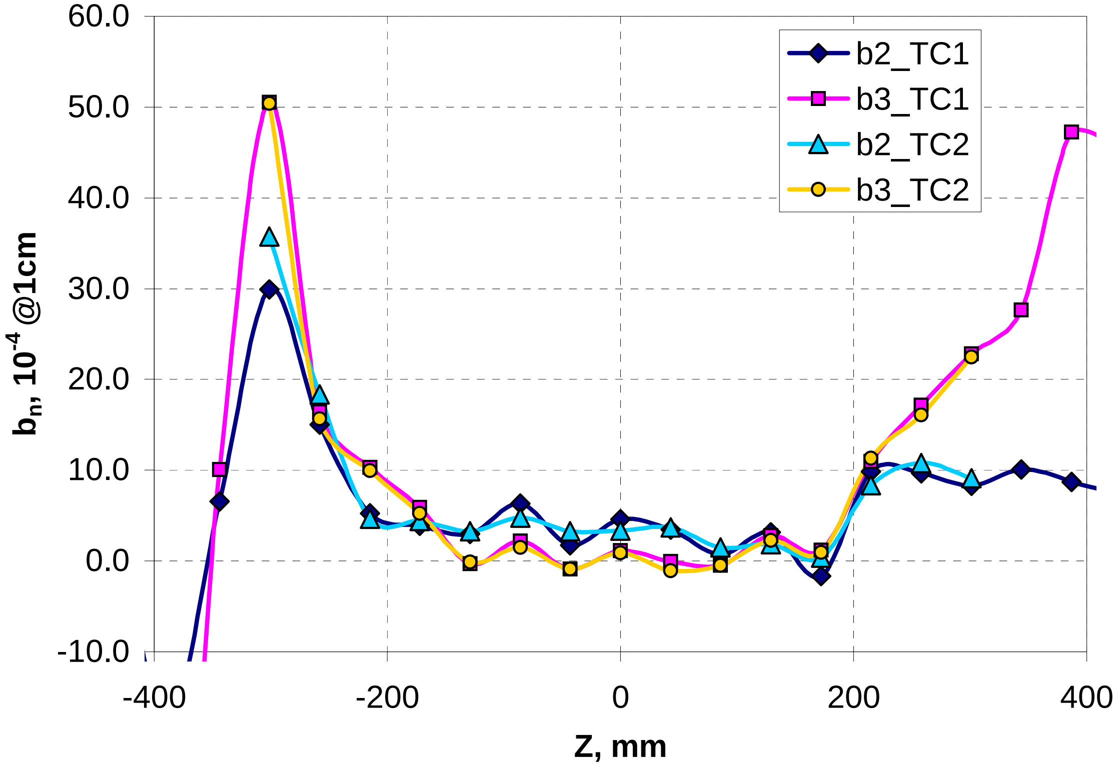

Figure 6. Normal quadrupole and sextupole along Z-axis.

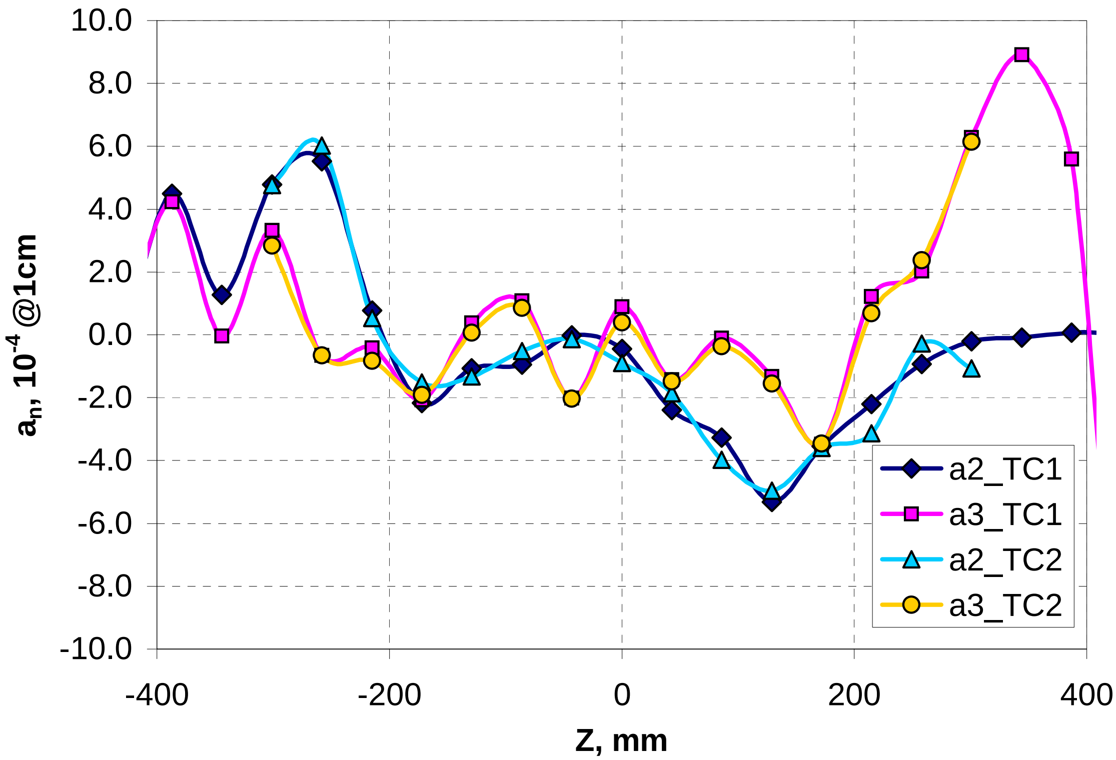

Figure 7. Skew quadrupole and sextupole along Z-axis.

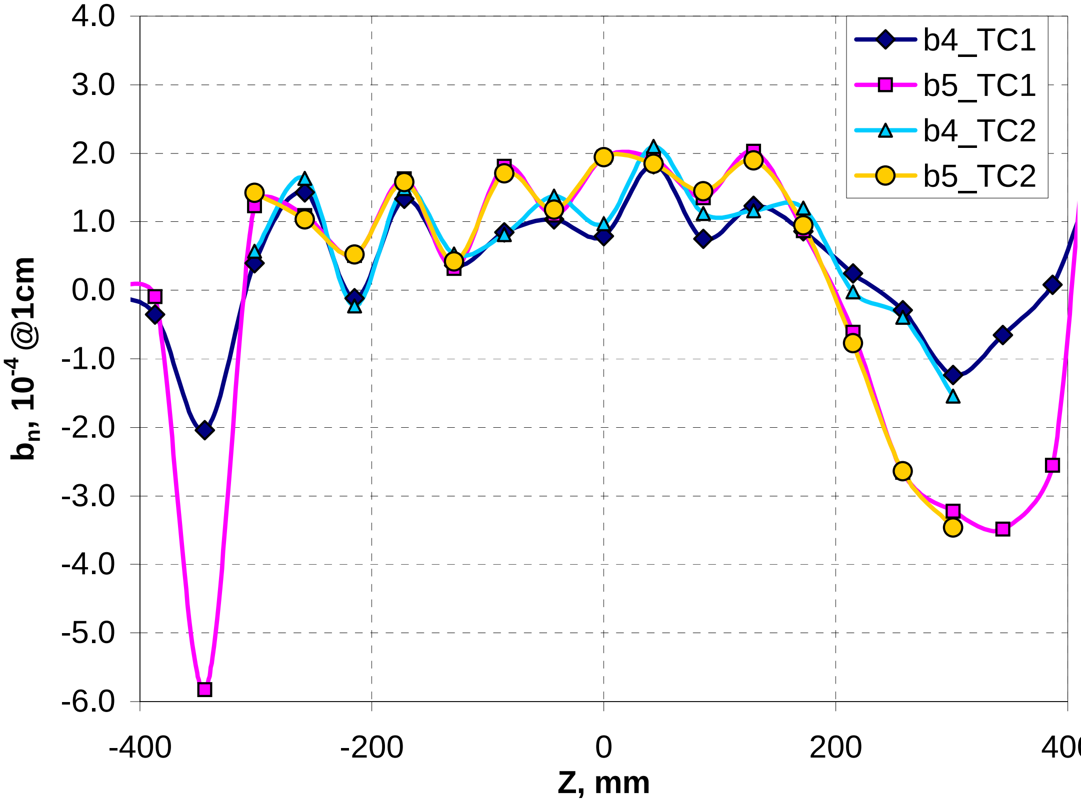

Figure 8. Normal octupole and decapole along Z-axis.

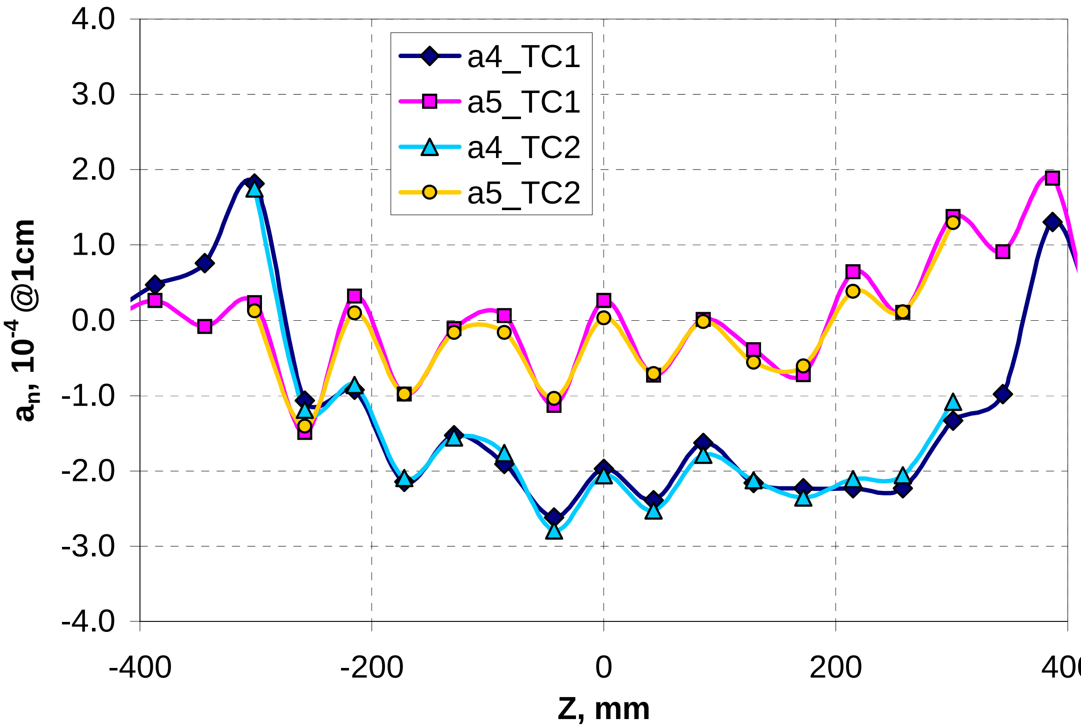

Figure 9. Skew octupole and decapole along Z-axis.

Hysteresys loops

The loop measurements were performed during TC1 in two consecutive cycles up to 16000 A with the ramp rates 20 A/s; up to 15000 A with the ramp rate 40A/s; and up to 13000 A with the ramp rate 80 A/s. There was observed an abnormal behavior with the sextupole being positive during the ramp-up and inversed sign during the ramp down, possibly attributed to large interstrand coupling currents in the cable. A stair-step measurement were performed in TC2 in order to acquire more data on this effect.

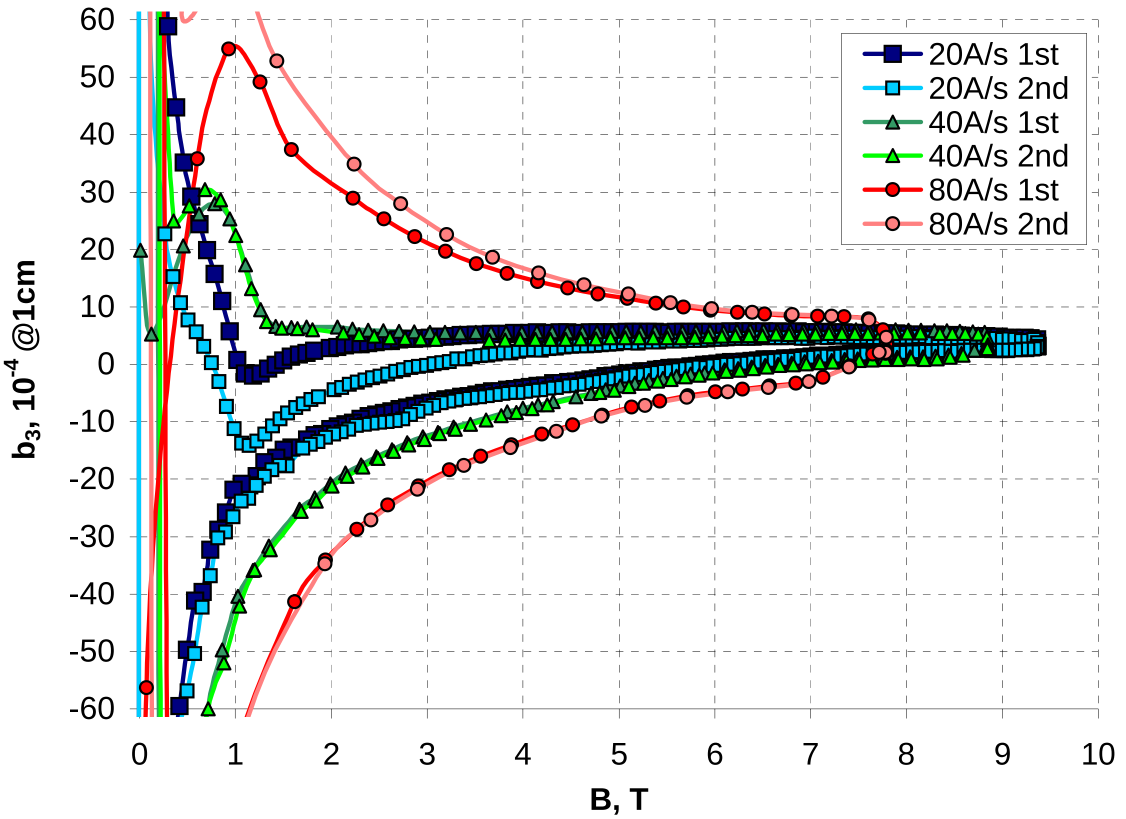

Figure 10. Sextupole loops. 1st and 2nd denotes the first and second ramps.

Stair-step measurement

The current was gradually raised up to 16000 A with 2000 A steps and then ramp down in the similar way. The ramp rate was 20 A/s and the dwell time at each step was 75 seconds. Figure 11. shows the sextupole harmonic as a function of field and Figure 12 shows sextupole harmonic and current as functions of time. From Figure 13 presenting a typical stair-step one can see that the sextupole decays at the end of the ramp during ~20 s and then slowly changes in the opposite direction with much longer time constant.

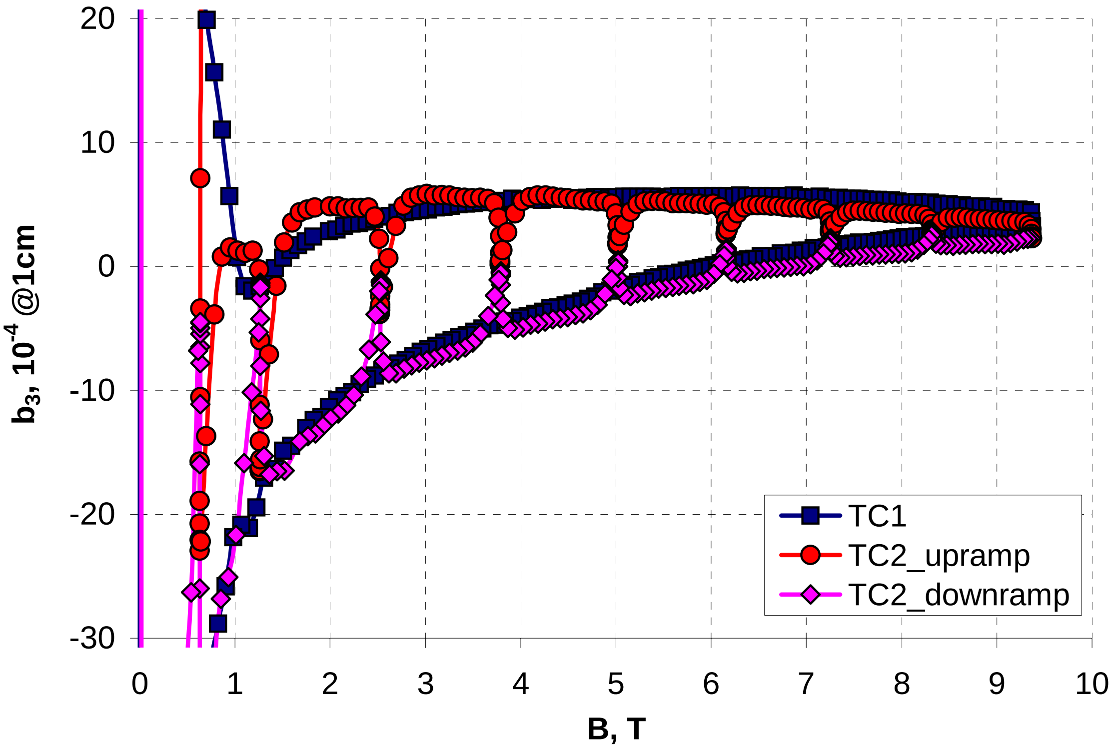

Figure 11. Sextupole as a function of field.

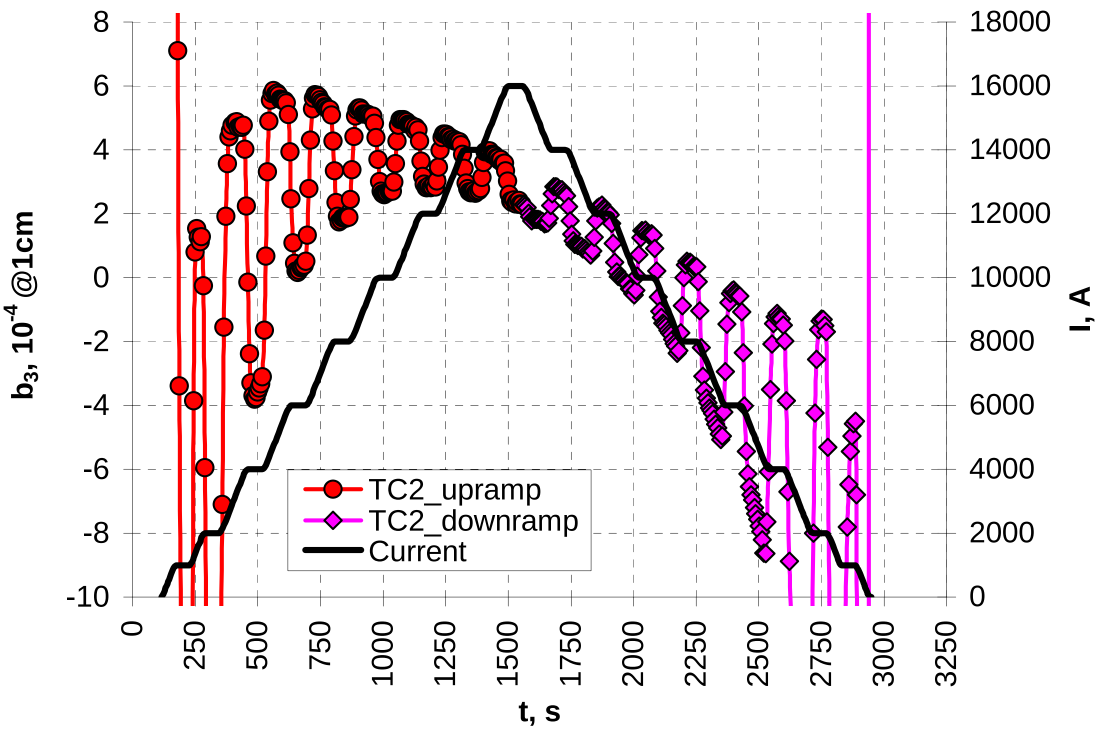

Figure 12. Sextupole and current as functions of time.

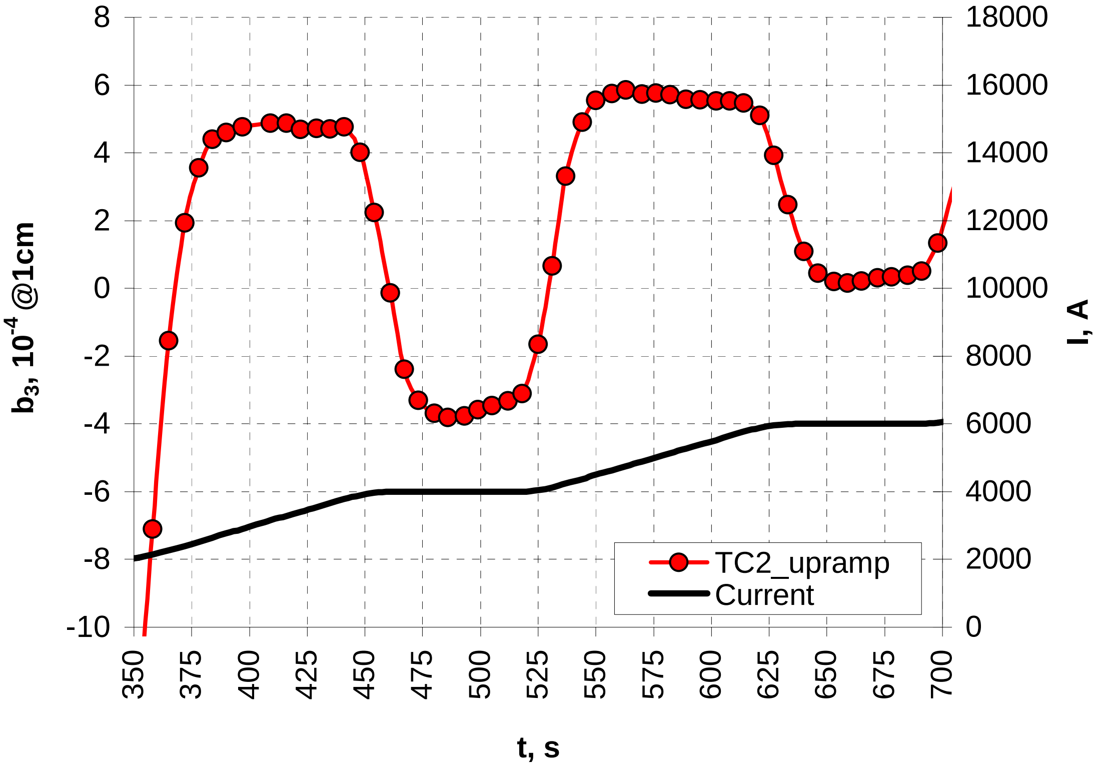

Figure 13. Sextupole and current as functions of time.

Snap-back measurements

Harmonics decay and snap-back were observed during 30 min at 2400 A plateau following the pre-cycle up to 12000 A. Figure 14 shows the whole sextupole and current profiles during the measurements and Figure 15 presents the sextupole and current on the plateau. Most of the sextupole decay happens within the first 20 min on the plateau. The kink at the end of the sextupole decay cannot be correlated with a similar disturbance in the current profile and is possibly related to redistribution of interstrand coupling currents in the cable.

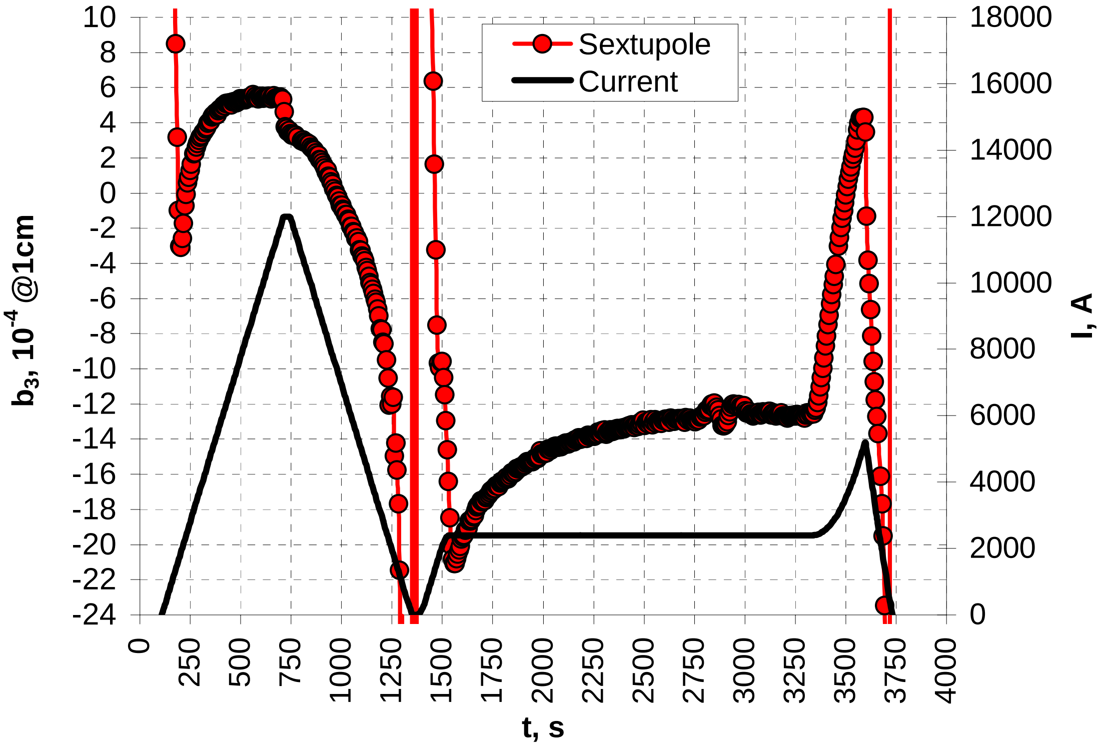

Figure 14. Sextupole and current as functions of time.

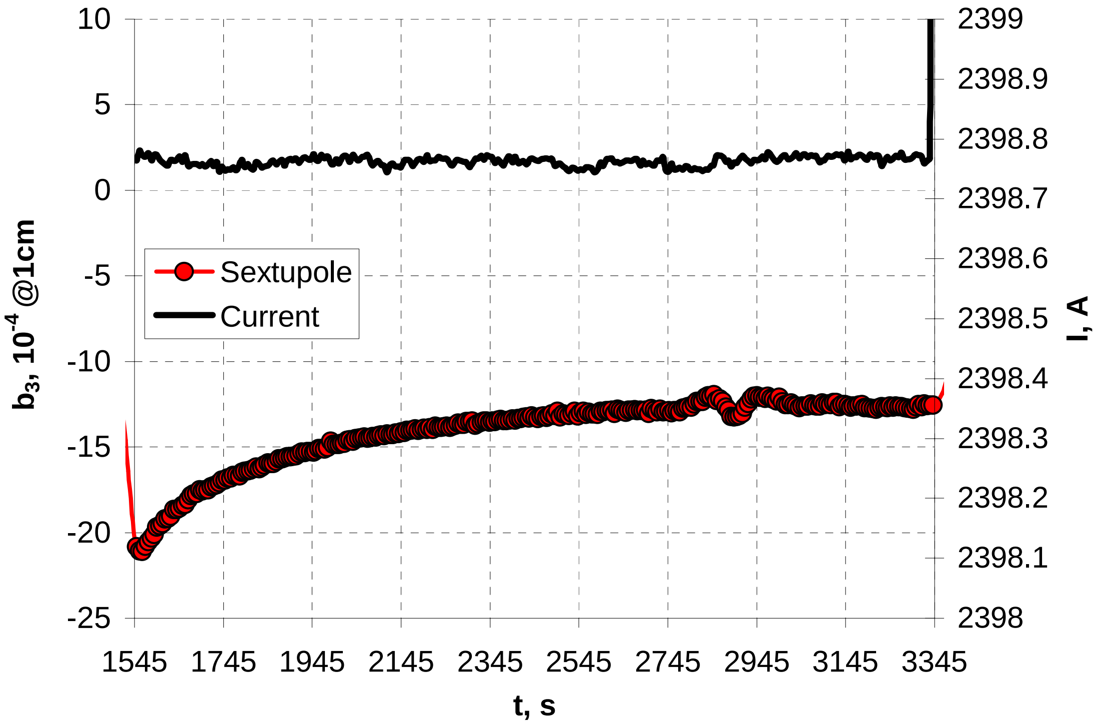

Figure 15. Sextupole and current as functions of time.

AC loss measurement

Energy Loss measurements were performed on HFDA05 at 4.5K using two HP3458A Digital Multimeters (dmm) setup to integrate over 1 power line cycle and sample at 60Hz. One dmm measured the magnet voltage and the second dmm measured the magnet current via the power system current transductor. The magnet was ramped between 500A and 6500A for all measurements. Five measurements were performed at each ramp rate of 75A/s, 100A/s, and 150A/s, and three pre-ramp cycles were performed before each new ramp rate.

The measured **Hysteresis = 876+/-153 Joules**
And the measured **Slope = 3.7+/-1.4J/A/s**

The following is a plot of the data (see previous page):

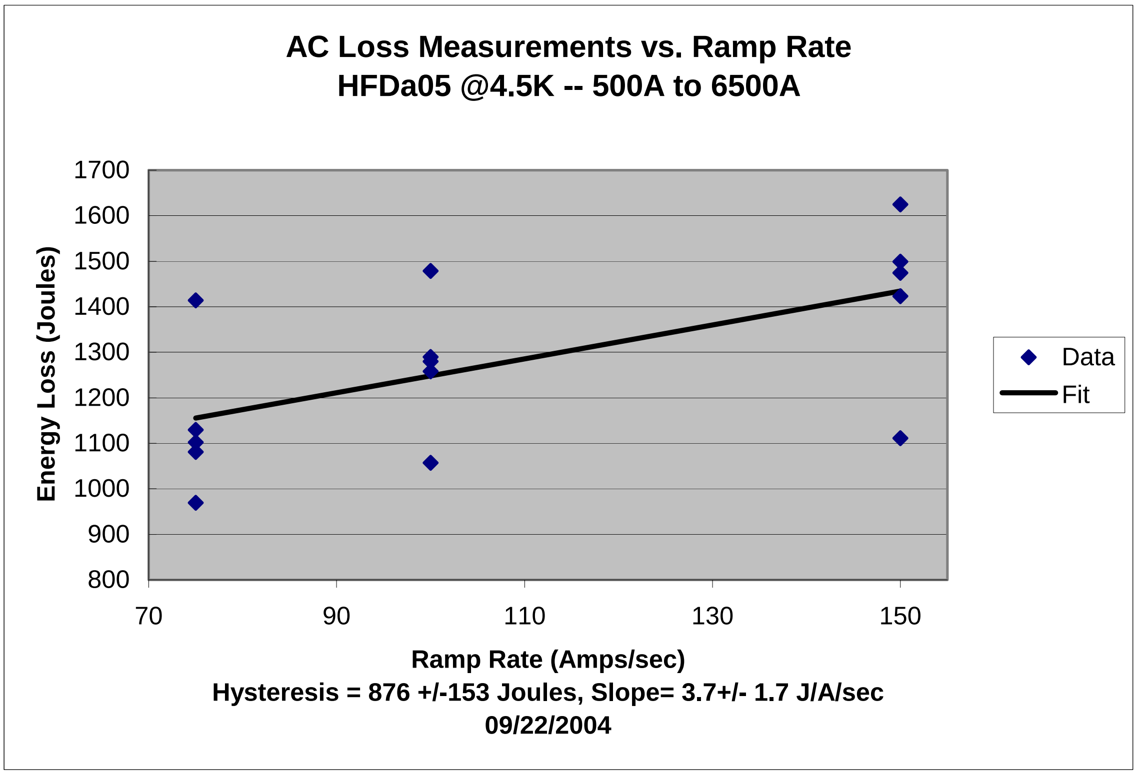

Figure 16. AC loss measurement plot as a function of current ramp rate.

Table 2.

HFDa05 Energy Loss Measurement Summery @4.5K -- 500Amps to 6500Amps

Ramp Rate(Amps/sec)	*Energy Loss(Joules)*	*Integral Volts*
75	969.306091	0.018708
75	1129.454468	0.032991
75	1101.85437	0.040475
75	1414.04187	0.08478
75	1081.328369	0.041065
100	1057.36792	-0.031926
100	1478.869019	0.087255
100	1289.883057	0.040526
100	1258.299927	0.046896
100	1279.642456	0.060683
150	1624.533569	0.073541
150	1474.229492	0.066617
150	1499.265137	0.064468
150	1422.926636	0.036959
150	1111.134033	0.009871

10. RRR measurement

The RRR measurement was performed on 9/26 – 10/02. The magnet was gradually warming up and meanwhile we recorded the whole coil voltage value generated by 10 A across the magnet. The results is summarized in Figure 17. The measured RRR value is 113 ±5.

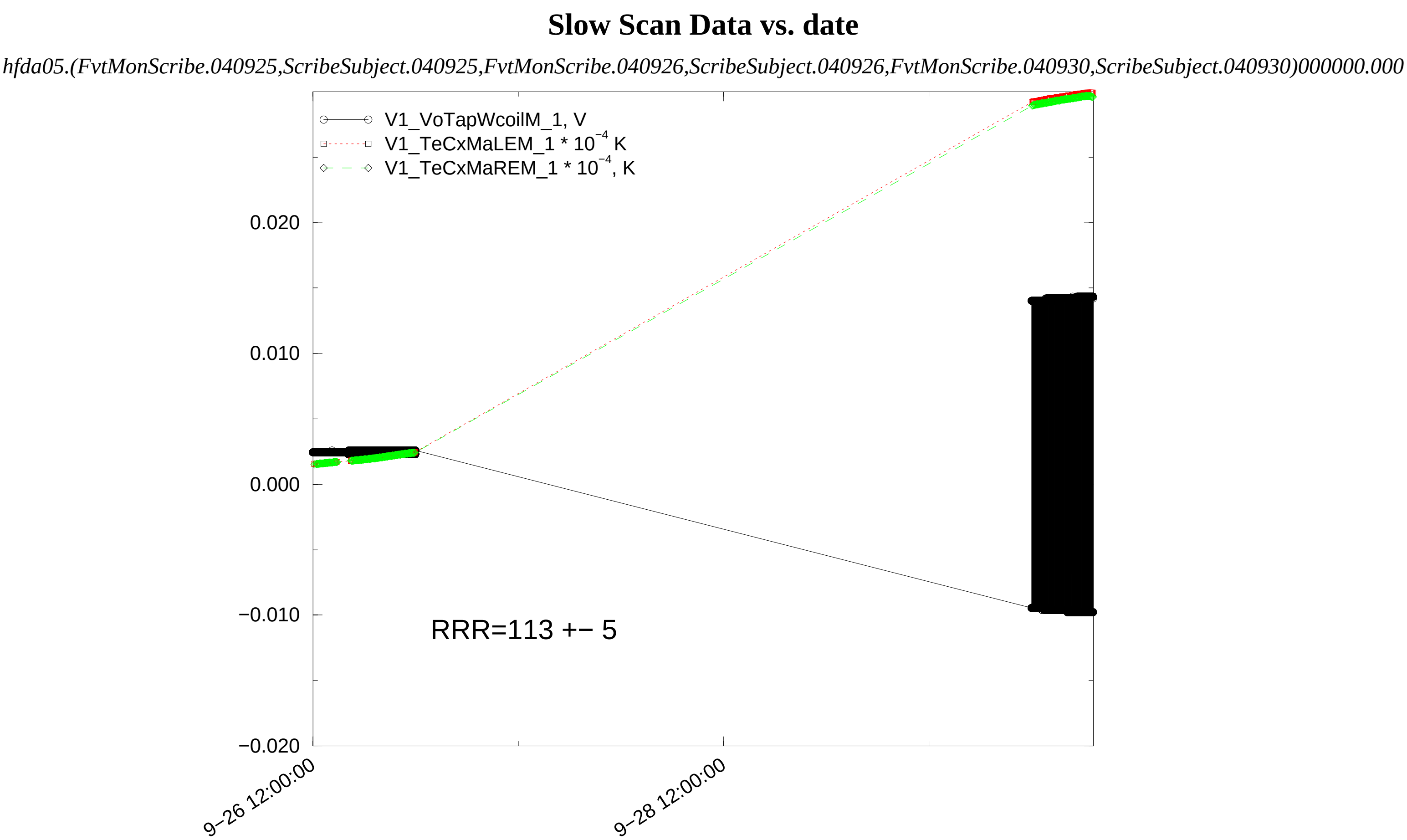

Figure 17. Magnet voltage is measured at applied current of 10 A as a function of time. Also the temperature of the magnet is also plotted.